REPORT No. 593

COOLING OF AIRPLANE ENGINES AT LOW AIR SPEEDS

By Theodore Theodorsen, M. J. Brevoort, and George W. Stickle

SUMMARY

A comprehensive experimental study has been carried out at full scale in the N. A. C. A. 20-foot wind tunnel, the general purpose of which is to furnish information in regard to the functioning of the power plant and propeller unit under different conditions. This report deals particularly with the problem of the cooling of an airplane engine on the ground. The influence of different nose forms, skirts, flaps, propellers, spinners, and special blowers has been investigated. Among the more interesting results are the demonstration of the comparative inefficiency of adjustable skirt flaps, the detrimental effect of small-diameter front openings of the cowling, and the very beneficial effect of a carefully designed airfoil section near the hub of the propeller. A small axial fan of simple construction was found to give efficient cooling on the ground.

INTRODUCTION

The problem of cooling an airplane engine on the ground obviously presents the greatest difficulty. The velocity head in the slipstream is then a minimum. The engine does not ordinarily develop its maximum horsepower, but the quantity of heat to be disposed of is not much reduced. A certain velocity head and a corresponding pressure drop are generally required to cool the engine satisfactorily. The problem then becomes one of providing a certain pressure drop for cooling on the ground or at a minimum air speed; cooling at higher speeds, of course, follows. Special devices, such as flaps on the skirt or fans in front of the cowling, are sometimes used to improve the cooling on the ground.

It has been shown (reference 1) that the cooling for the cruising condition is almost exclusively a function of air speed, the effect of the propeller slipstream velocity being of little importance. At low air speeds the situation is different; the cooling is largely dependent on the propeller effect. On the ground the cooling depends, of course, entirely on the propeller. The subject of primary interest in this paper is the study of the factors affecting the cooling on the ground.

ANALYSIS OF THE PROBLEM

It was shown in reference 1 that the cooling of an engine is a function of the pressure drop Δp across the cylinder bank. Most of the tests reported in this paper were extended down to the minimum tunnel speed. This minimum tunnel speed corresponds to the effect of the local propeller slipstream on the closed-circuit tunnel and is approximately 20 miles per hour, low enough to permit an extrapolation of results to the condition of zero air speed.

At very low air speeds the effect of the slipstream dominates the situation, the propeller functioning as a low-pressure blower. For the condition of zero air speed, the quantity $\Delta p/n^2$ has been chosen as the characteristic function, this quantity being independent of the revolution speed of the propeller. The square root

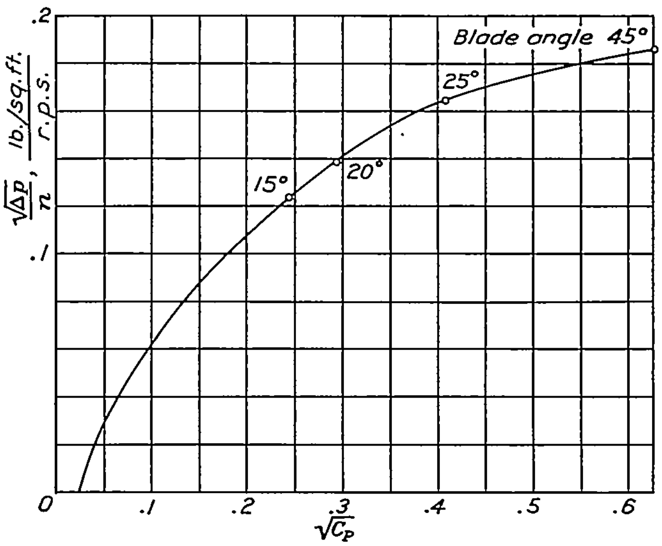


Figure 1.—Typical curve showing the dependency of $\sqrt{\Delta p}/n$ on $\sqrt{C_P}$ for $V/nD=0$.

of this quantity is plotted against the advance-diameter ratio V/nD. Plots of this type conveniently picture the relationship between the available pressure and the air speed at any combinations of the other variables and show directly the primary results of the present investigation.

In order to apply the results for the condition of zero air speed, there need be known only the revolution speed n of the propeller at any particular angle of attack. For this purpose it is very convenient to plot the pressure function $\Delta p/n^2$ against the nondimensional power coefficient C_P at zero air speed, defined as

$$C_P=\frac{P}{\rho n^3 D^5}=\frac{2\pi Q}{\rho n^2 D^5}$$

where P is the power and Q the torque of the propeller. A curve of this type is illustrated in figure 1

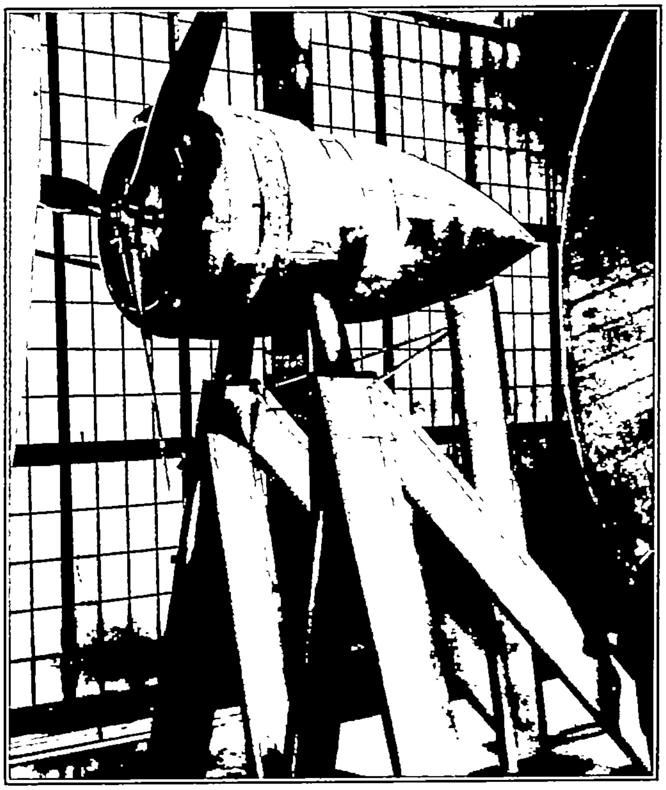


FIGURE 2.—The N. A. C. A. fan installed on the engine.

for a particular propeller over the entire range of blade-angle settings. The ordinate used is actually the square root of the pressure function, or $\sqrt{\Delta p}/n$, and the abscissa is similarly $\sqrt{C_P}$. At a given power and propeller diameter the revolution speed is known at each blade angle and, in consequence, also the value of Δp. The selection of the blade angle producing the highest pressure drop Δp is identical with the selection of the point on the curve having the greatest slope for a straight line drawn from the point to the origin. It is found, in general, that this condition corresponds to that of the maximum speed of the engine and a resulting minimum propeller blade-angle setting. In order to represent the degree of transmissibility of the baffles, a quantity K, designated "conductivity," has been defined in reference 1 as

$$K=\frac{Q}{FV\sqrt{\frac{\Delta p}{q}}}$$

where Q is the quantity of the air passing through the baffles per second.

F, the cross section of the nacelle as a reference area.

q, the velocity head.

and V, the velocity of the air stream.

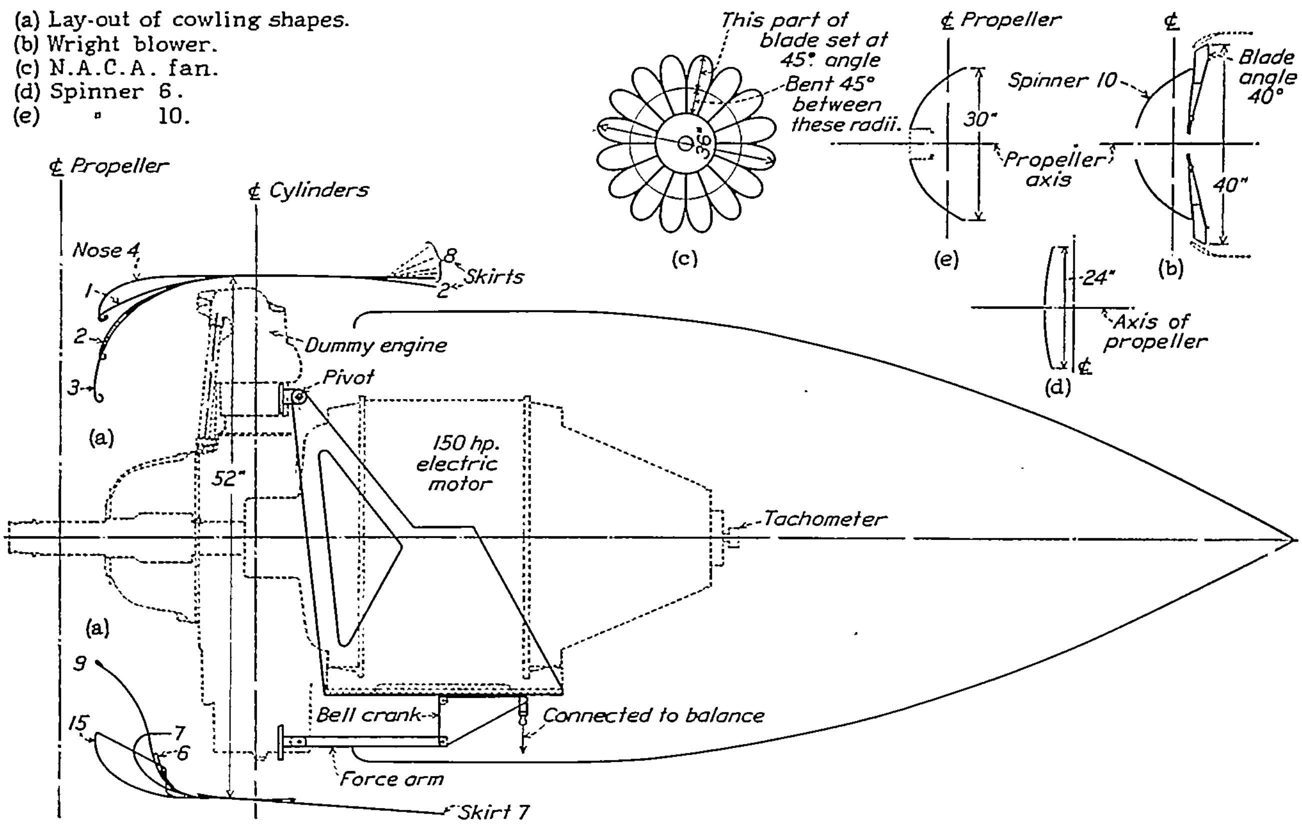


FIGURE 3.—Lay-out of the test arrangements.

DESCRIPTION OF EQUIPMENT

This investigation was conducted in the N. A. C. A. 20-foot tunnel, which, with its equipment, is described in detail in reference 2. The general arrangement of the test model is shown in figure 2. Detailed description of the particular equipment used is given in reference 3. Figure 3 (a) shows the various nose cowlings and skirts employed in the present investigation, together with other equipment used. Figure 3 (b) shows an experimental blower used in conjunction with nose 15 especially designed to house it. Figure 3 (c) shows an axial fan of simple construction hereinafter referred to as the "N. A. C. A. fan." Figure 3 (d) shows a circular flat disk 24 inches in diameter, which was attached to the front of the propeller in some of the following tests and is referred to as "spinner 6." Figure 3 (e) shows a normal type of spinner which was actually an integral part of the experimental blower shown in figure 3 (b) but which was sometimes used separately and designated "spinner 10." Figure 4 is a photograph of the four propellers with the designations employed in this report. The following table is given for reference from the associated propeller report (reference 3). A photograph of the experimental blower is shown in figure 5; the N. A. C. A. fan may be seen just behind the propeller in figure 2.

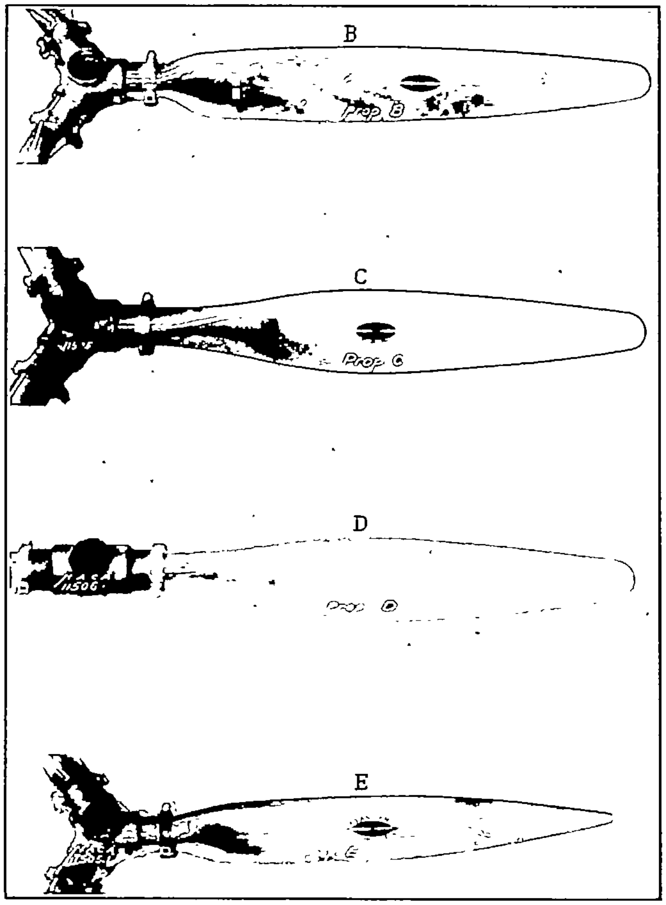


FIGURE 4.—Propellers tested.

PROPELLER DATA

Propeller designation	Drawing	Number of blades	Diameter (feet)	Type	Remarks	Airfoil section
A	Hamilton-Standard 6101-0	3	10.08	Controllable		Clark Y.
B	Hamilton-Standard 1C1-0	3	10.04	Adjustable		Do.
B_x	Hamilton-Standard 1C1-0 (modified)	3	10.04	do	Pitch decreased from the 70 percent radius to the tip.	Do.
C	Navy plan form 5868-9	3	10.02	do		Do.
D	Navy plan form 5868-9	2	10.00	do	Same as C except 2 blades	Do.
E	Navy plan form 3790	3	9.04	do		R. A. F.-6.

RESULTS

Figures 6, 7, 8, and 9 show the basic results of the investigation. Code numbers appear showing different arrangements. For example, arrangement 6–2–B–3–0 indicates that nose 6, skirt 2, propeller B, inner cowling 3, and no spinner were used. The ordinate used is $\sqrt{\Delta p}/n$ and the abscissa is the quantity V/nD, as prescribed in the preceding analysis. The range presented is actually the entire range of flight speed and it is noted that the slipstream effect gradually diminishes as the speed is increased. The curves asymptotically approach straight lines through the origin.

The series given in figure 6 shows, in particular, the effect of the blade-angle setting, the propellers B, B_x, C, D, and E being used on the most neutral cowlings composed of noses 6 or 7 and skirt 2. It is noticed that propeller B, or B_x, which has a good airfoil section near

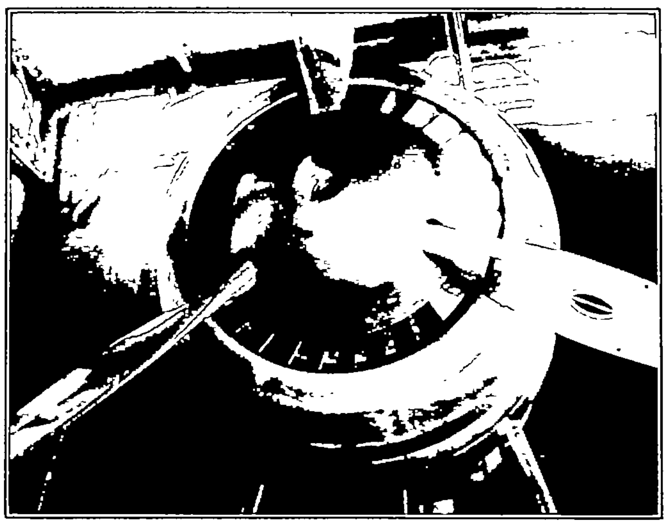


FIGURE 5.—Wright blower with propeller C and spinner 10.

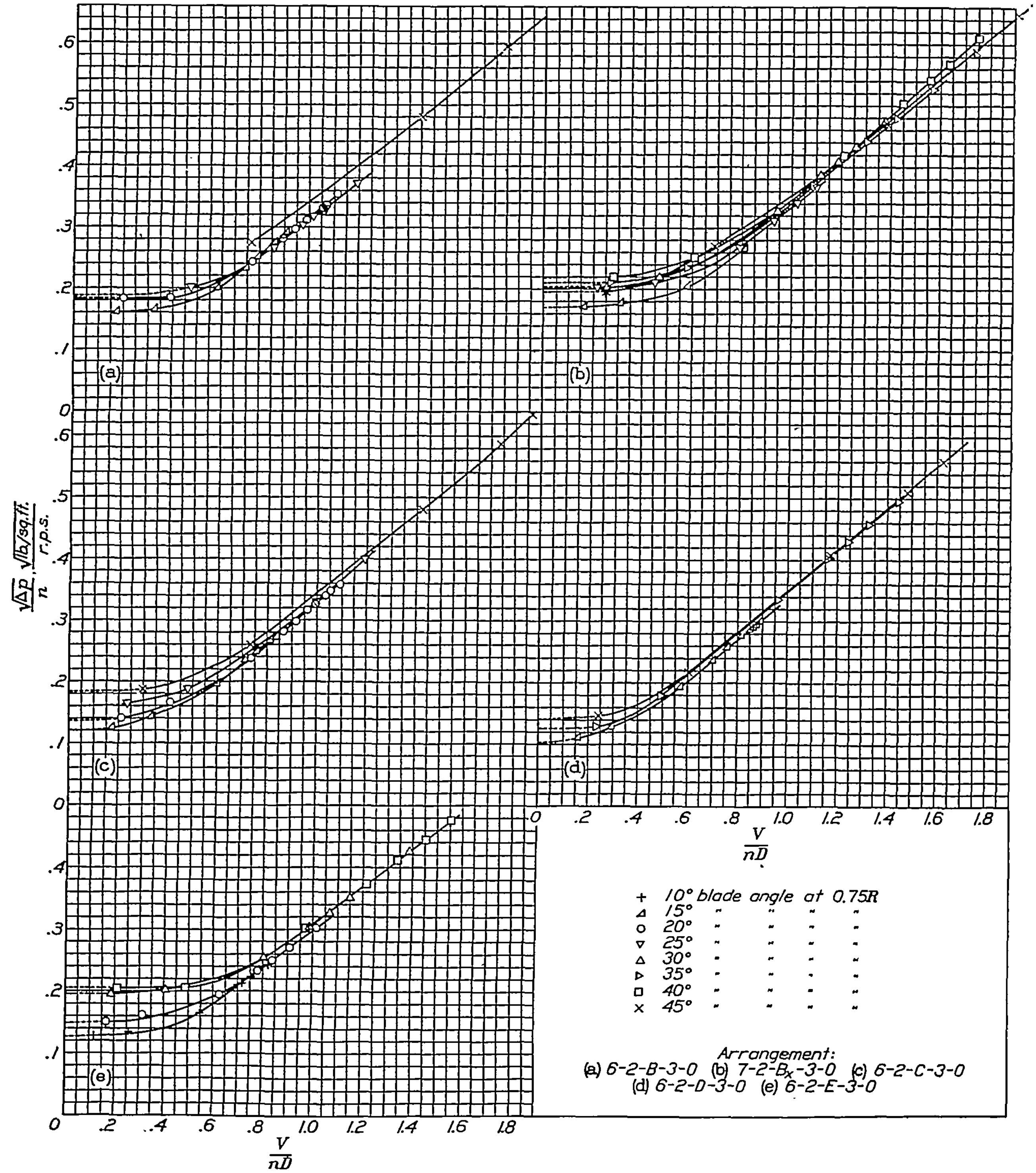


FIGURE 6.—Dependency of $\sqrt{\Delta p}/n$ on V/nD for several propellers at various blade angles.

the hub, is superior to the almost identical propeller C with a round hub section. The three-blade propeller C, and the two-blade propeller D, having identical blade sections, give available pressure drops almost proportional to the number of blades.

The next series (fig. 7) gives the effect of the various noses tested, the propellers used being restricted to B and C at blade angles of 25° and 35°. The result of most immediate interest is the apparent inferior cooling properties of the noses 3 and 9, the available pressure drop Δp being of the order of one-half or less of those obtained on the normal designs. It is further noticed that nose 4, which is characterized by a very flat nose section pointing radially inward, shows without exception the highest available pressure at the ground point. Noses 6 and 7, which are among the best at cruising condition (reference 1), appear, however, to be fairly close to the maximum.

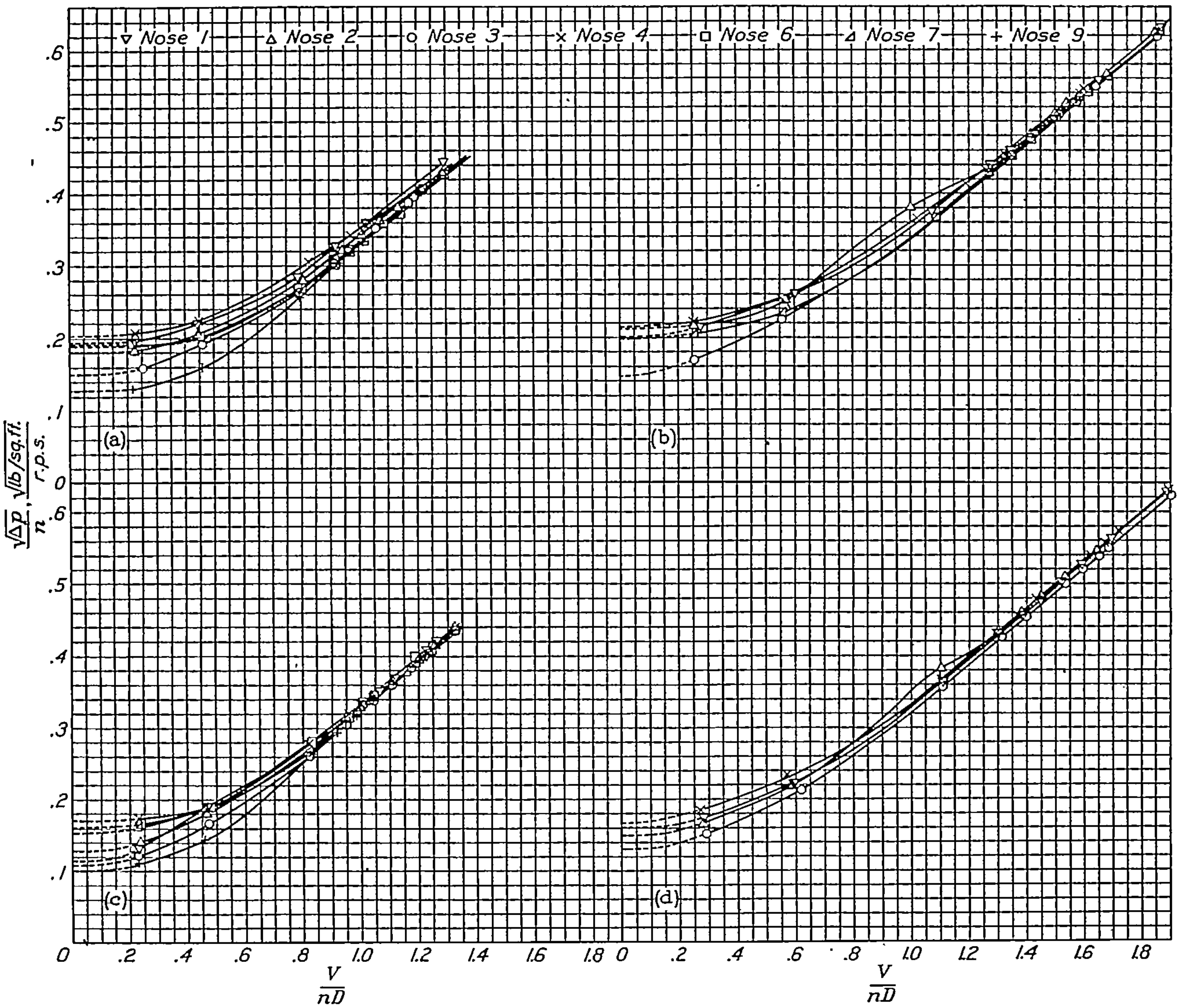


FIGURE 7.—Dependency of $\sqrt{\Delta p}/n$ on V/nD for several nose shapes on different propeller arrangements; skirt 2.

Figure 8 reproduces the experimental results in regard to the much-discussed problem relating to the use of cowling flaps. The flaps used were of normal design, 5 inches long, and were given successive increases in flap angle corresponding to flares of ½, 1, 2, and 3 inches at the rear end. The results show that the gain in available pressure is in the order of 15 percent as compared with the unflared skirt. This result is interesting insofar as it shows the performance of normal short flaps to produce a suction at the slot. In contrast, it is seen that skirts 7 and 8 represent a decided gain over the narrower skirt 2, this latter gain being in the order of 50 percent. Similar results are available for other propellers and blade angles and show substantial agreement.

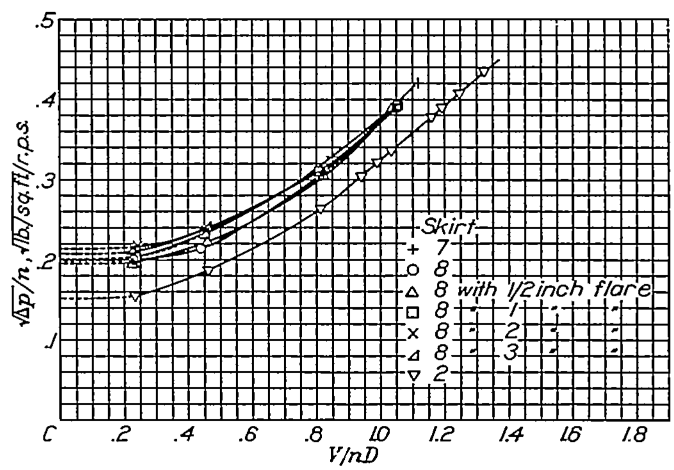


FIGURE 8.—Dependency of $\sqrt{\Delta p}/n$ on V/nD for several skirts with nose 7 and propeller C set 25° at 0.75R.

Figure 9 shows the results of a related investigation on the effect of fans or blowers, presented for comparison in conjunction with some other typical cases. The most interesting result is the remarkable effectiveness of the very simple N. A. C. A. fan. The Wright blower is seen to be very inefficient, the pressure function remaining below 0.2, and is inferior to the propeller B alone.

Improved cooling on the ground is generally attained at some loss of efficiency at high air speeds. This loss is evident from the associated net-efficiency curves of figure 9. It is noticed that nose 7 with spinner 10, which gives poor cooling on the ground, shows the highest efficiency in flight conditions; whereas the N. A. C. A. fan, being superior for cooling, shows the lowest net efficiency.

The following table shows the pressure constants for the various propeller noses and skirts for the condition of cooling on the ground.

VALUES OF PRESSURE CONSTANT $\frac{\sqrt{\Delta p}}{n}$ AT $\frac{V}{nD}=0$

Blade angle (degs.)		Propeller B				Propeller B_x						Propeller C					Propeller D			Propeller E				Remarks
		15	20	25	35	15	25	30	35	40	45	15	20	25	35	45	15	35	45	10	20	30	40	
Nose	Skirt																							
1	2	-----	-----	0.193	0.201	-----	-----	-----	-----	-----	-----	-----	-----	0.114	0.160	-----	-----	-----	-----	-----	-----	-----	-----	
2	2	-----	-----	.180	.212	-----	-----	-----	-----	-----	-----	-----	-----	.128	.149	-----	-----	-----	-----	-----	-----	-----	-----	
3	2	-----	-----	.150	.146	-----	-----	-----	-----	-----	-----	-----	-----	.108	.129	-----	-----	-----	-----	-----	-----	-----	-----	
4	2	-----	-----	.202	.214	-----	-----	-----	-----	-----	-----	-----	-----	.170	.166	-----	-----	-----	-----	-----	-----	-----	-----	
6	2	0.160	0.183	.188	-----	-----	-----	-----	-----	-----	-----	0.121	0.136	.160	-----	0.184	0.104	0.127	0.142	0.127	0.148	0.195	0.205	
7	2	-----	-----	.190	.198	0.170	0.202	0.204	0.210	0.218	0.195	-----	-----	.152	-----	-----	-----	-----	-----	-----	-----	-----	-----	
9	2	-----	-----	.128	-----	-----	-----	-----	-----	-----	-----	-----	-----	.100	-----	-----	-----	-----	-----	-----	-----	-----	-----	
7	7	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	0.200	-----	-----	-----	-----	-----	-----	-----	-----	-----	
7	8	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	.199	-----	-----	-----	-----	-----	-----	-----	-----	-----	
7	8	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	.195	-----	-----	-----	-----	-----	-----	-----	-----	-----	½-inch flare.
7	8	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	.201	-----	-----	-----	-----	-----	-----	-----	-----	-----	1-inch flare.
7	8	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	.214	-----	-----	-----	-----	-----	-----	-----	-----	-----	2-inch flare.
7	8	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	.208	-----	-----	-----	-----	-----	-----	-----	-----	-----	3-inch flare.
15	2	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	0.150	-----	-----	-----	-----	-----	-----	-----	-----	-----	
15	2	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	.195	-----	-----	-----	-----	-----	-----	-----	-----	-----	Spinner 10 and Wright blower.
15	2	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	.243	-----	-----	-----	-----	-----	-----	-----	-----	-----	N. A. C. A. fan.
7	2	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	.183	-----	-----	-----	-----	-----	-----	-----	-----	-----	Spinner 10.

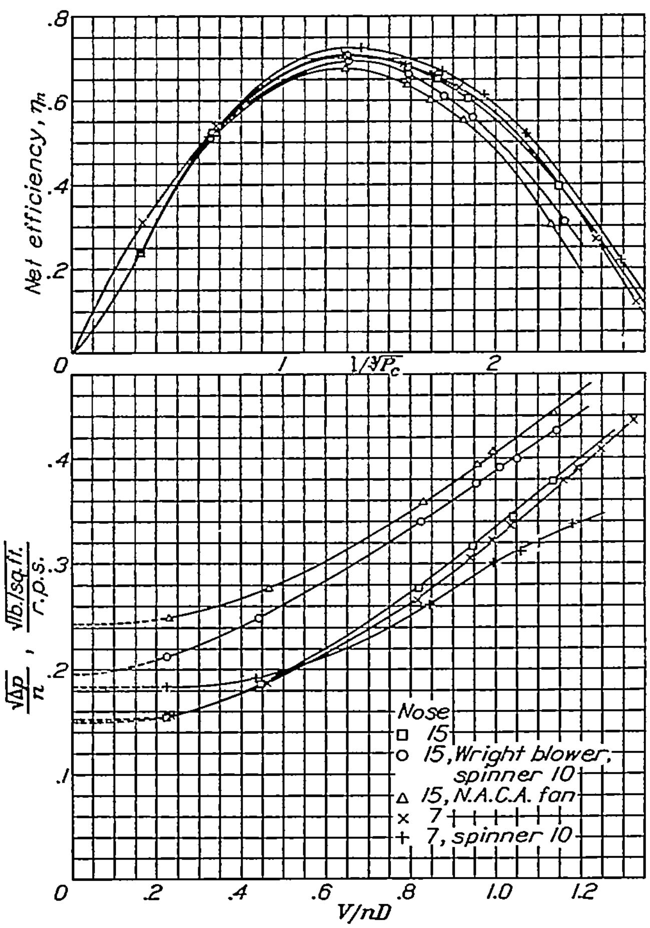
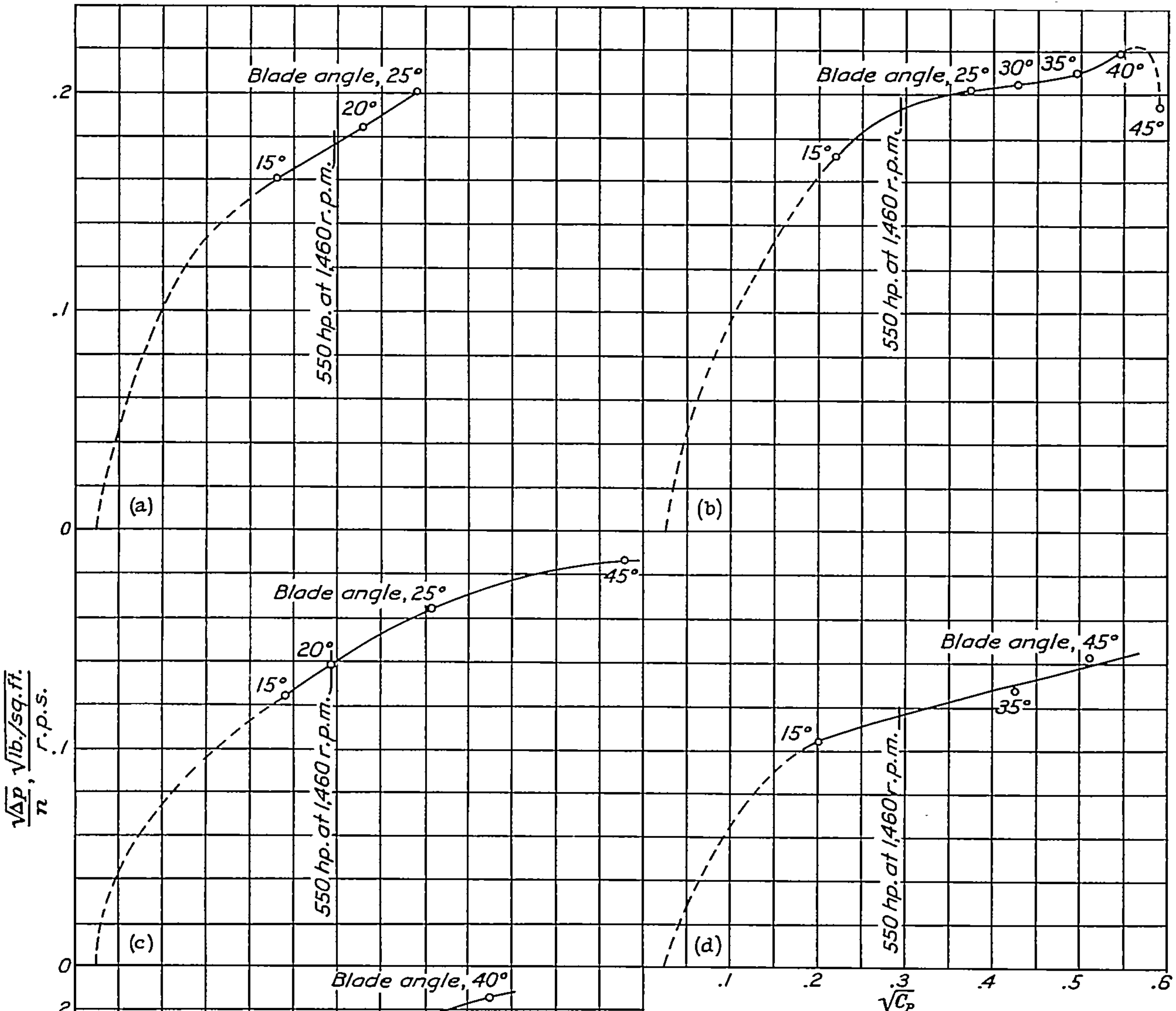
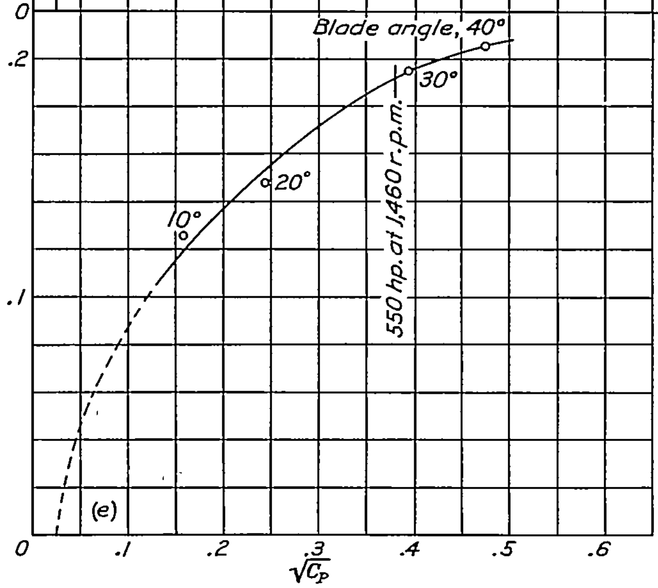


FIGURE 9.—Dependency of $\sqrt{\Delta p}/n$ on V/nD and of η_n on $1/\sqrt[3]{P_c}$ for propeller C set 25° at 0.75R with different test units.

Figure 10 shows the pressure function $\sqrt{\Delta p}/n$ on the ground for the five propellers. As explained in the previous analysis, the slope of a line drawn from any particular point on this curve to the origin is proportional to the square root of the available pressure Δp, the maximum slope giving the greatest available pressure on the ground. It is seen that this point, at which the highest pressure occurs in most cases, corresponds to a blade angle of less than 15°. Assuming a 550-horsepower engine with a 10-foot controllable propeller, the minimum blade angle permissible to prevent excess speed is about 19°, which corresponds to 1,460 r. p. m. of the propeller. The reason for the more effective action of the propellers occurring at low pitch settings lies in the fact that the propeller loading is concentrated more toward the hub. The practical conclusion is that, in order to obtain maximum cooling on the ground, the propeller should be given a minimum blade-angle setting corresponding to maximum engine speed.

Thus far the discussion has dealt entirely with the pressure drop and the factors affecting it. Results of some related tests of temperature measurements that were conducted at the same time will now be presented. It has previously been found (reference 1) that an available pressure drop of 10 pounds per square foot across the engine, if properly used, will provide sufficient cooling in accordance with present-day practice. It was found that a very definite relation between the rear temperature and the pressure drop exists; the front temperature was shown to depend on several



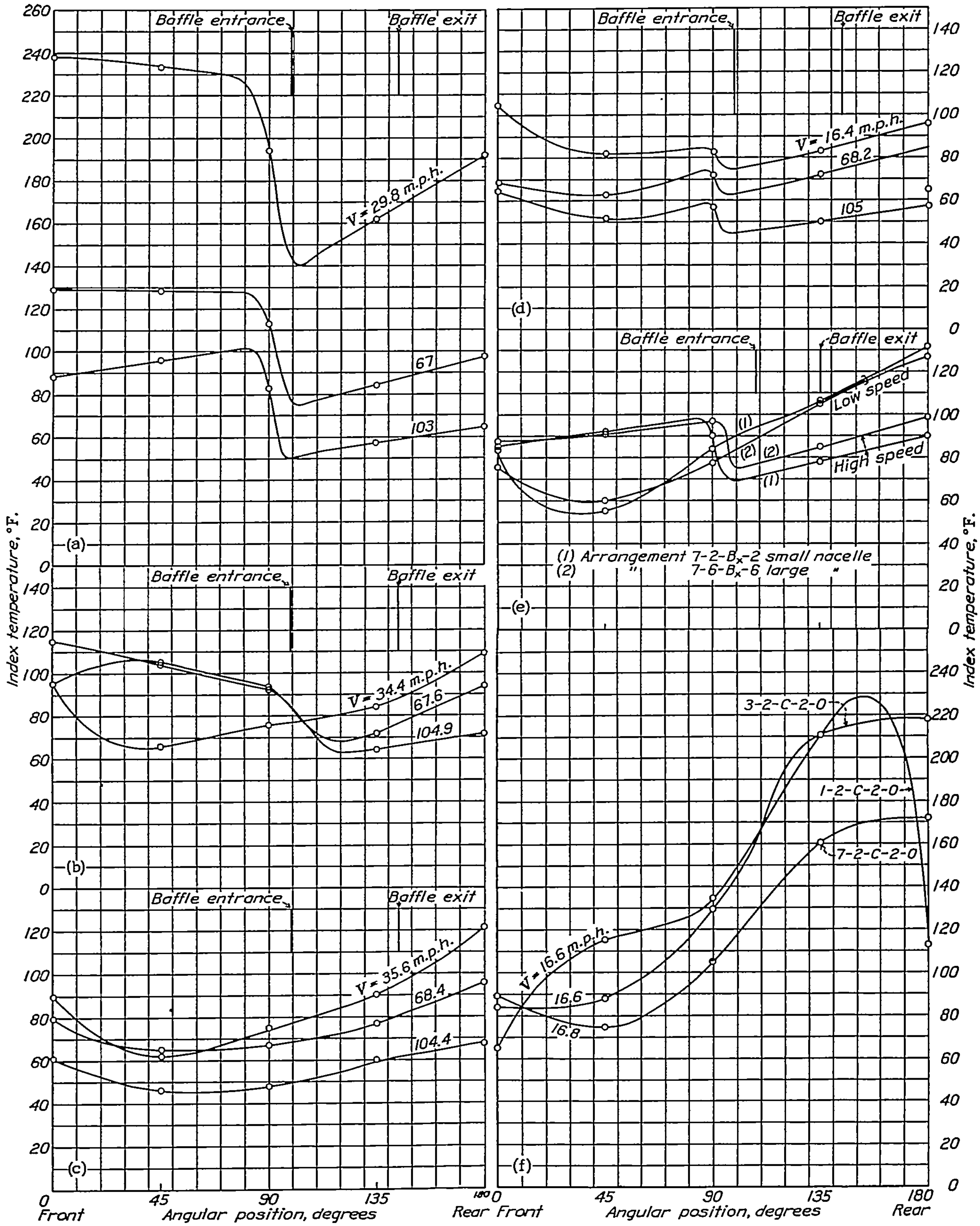


(a) Arrangement 6-2-B-3-0. (b) Arrangement 7-2-B_x-3-0.
(c) Arrangement 6-2-C-3-0. (d) Arrangement 6-2-D-3-0.
(e) Arrangement 6-2-E-3-0.

FIGURE 10.—Dependency of $\sqrt{\Delta p}/n$ on $\sqrt{C_P}$ for $V/nD=0$ at different blade-angle settings at $0.75R$.

other factors. In the present paper, the temperature distribution around the circumference of a cylinder is shown in more detail. The particular cylinder on which the measurements were made contained an electric heater, the output of which was kept constant at 1.75 kilowatts, the temperature thus being a direct measure of the heat transmission. This temperature is referred to as an "index temperature."

Figure 11 shows selected examples of the temperature distribution around a heated cylinder at various air speeds and for different arrangements. For the cases shown in figure 11 it is necessary to realize that the high temperatures shown at the lowest air speeds are somewhat misleading, being directly a consequence of the very low revolution speeds of the propeller in this condition. Comparison with results in reference 1 of the available pressure on the ground and at low speeds indicates that the extrapolated values of the temperatures at zero air speed would not be much in excess of those obtained at the lowest air speed. The revolution speeds employed in the tests were roughly of the order of one-half of those on conventional installations since



(a) Arrangement 7-2-0-3-0; $K=0.0424$.
(b) Arrangement 7-2-B-3-0; $K=0.0424$.
(c) Arrangement 7-2-B-3-6; $K=0.0424$.
(d) Arrangement 15-2-C-3-10 (Wright blower); $K=0.0424$.
(e) High and low speed for two arrangements; $K=0.0909$.
(f) Baffles removed from arrangement of three nose shapes; $K=0.3$ to 0.6.

FIGURE 11.—Distribution of index temperature around the cylinder for various arrangements.

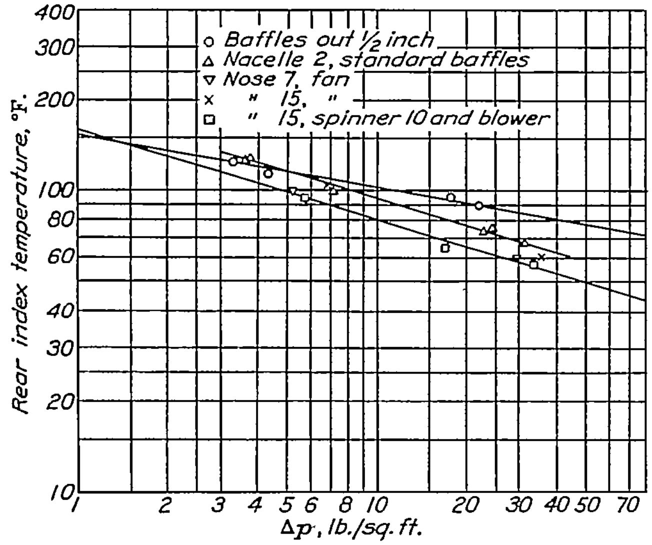
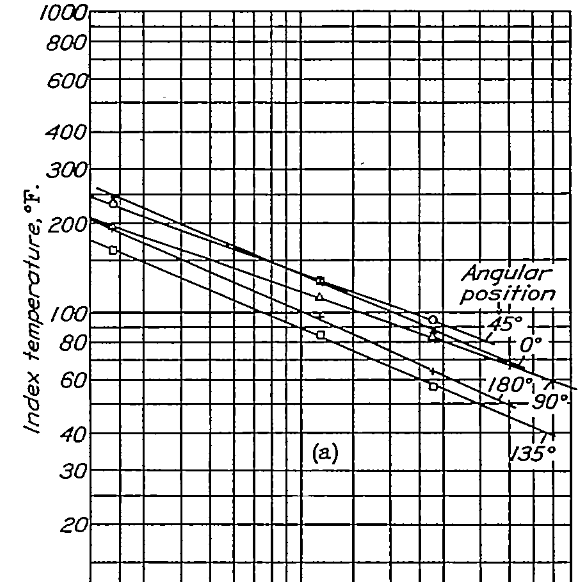
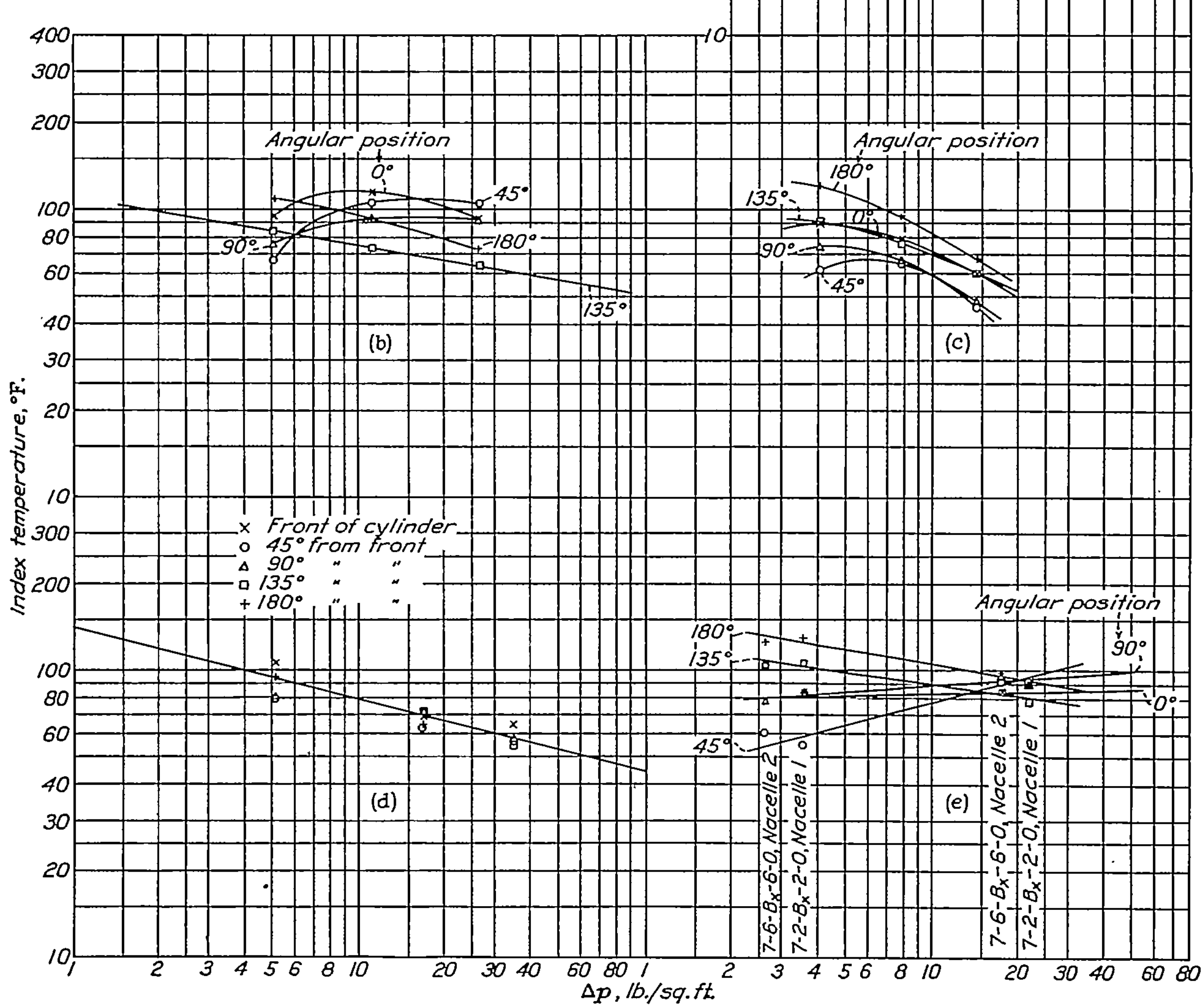


FIGURE 12.—Dependency of index temperature on Δp for several nose shapes, fans, and conductivities.

(b) Arrangement 7-2-B-3-0; K=0.0424.
(d) Arrangement 15-2-C-3-10 (Wright blower); K=0.0424.
(a) Arrangement 7-2-0-3-0; K=0.0424.
(c) Arrangement 7-2-B-3-6; K=0.0424.
(e) High and low speed for two arrangements; K=0.0909.

FIGURE 13.—Dependency of index temperature on Δp for various arrangements.

only about one-eighth of the power was used. As a result, the ground cooling pressure amounted to about one-quarter of actual values and the coefficients of heat transmission to approximately $4^{-0.3}$, or about two-thirds of the values at the proper propeller speed. As a consequence the temperatures measured are about 50 percent in excess of the values that would be obtained for the same heat output at normal propeller speeds. The first four sets of curves of figure 11 are for the standard baffling, $K=0.0424$, all taken on the small nacelle. In figure 11 (a) is shown a case of propeller off; the three curves show three different tunnel speeds. In figure 11 (b) is shown a case with propeller B and in figure 11 (c) a flat spinner has been added. Note the very beneficial effect of the spinner on the front temperatures. In figure 11 (d) the results are given for a special test series on a Wright experimental blower. The next figure, 11 (e), shows the temperature distribution obtained with a larger gap between the cylinder and the baffles; $K=0.0909$ at two air speeds and with both nacelles. Note the large increase in the rear temperatures. Figure 11 (f) shows the distribution for minimum air speed for the case of baffles removed: $K=0.3$ to 0.6.

Figure 12 shows the relationship between the rear temperature and the pressure drop across the cylinder bank as resulting exclusively from the change in the air speed. The slopes of the resultant curves are somewhat inconsistent, lying apparently between -0.2 and -0.3.

Figure 13 is given to indicate the exponents of the temperature-pressure relationship at various angular positions around the cylinder. It is apparent that the frontal temperature is very independent of the pressure drop. Figure 13 (e) shows a particularly irregular result; the heat transmission on the front actually increasing at low tunnel speeds, especially at the 45° position, probably indicating a peculiar flow condition.

GENERAL CONCLUSIONS

1. A blade section of proper airfoil shape near the hub is found to be effective in producing increased cooling on the ground, being far superior to the conventional round shank. The N. A. C. A. fan of very simple construction gave the highest observed available pressure; it appears, however, that this result could be equaled by improving the design of the airfoil section near the hub.

2. Adjustable skirt flaps were found to increase the pressure drop in the order of 15 percent. Flaps are not recommended except for very loosely baffled or unbaffled engines.

3. The design of the nose of a cowling is of some influence in regard to the cooling at the ground point. Noses with a small frontal opening were found to be inferior and are not recommended. A nose design with a radial inward bend of the leading edge (nose 4) was found to be superior to, but only slightly better than, the normal designs (nose 7) recommended for cruising conditions.

4. The charts given in the paper for a number of conventional propellers indicate the most efficient blade-angle setting for obtaining the best cooling at the ground point. The angle is apparently a function only of the permissible maximum engine speed, which was found to correspond to a blade angle of about 20°.

5. No very general conclusion is possible in regard to the temperature distribution. The beneficial influence of a tight baffling has been demonstrated. A flat plate, or spinner, in front of the propeller hub has been demonstrated to improve very effectively the cooling on the front. The apparently inconsistent results often obtained on the cooling of the front of the cylinder seem to indicate that several unknown factors are involved and leave a field for future study.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., *June 2, 1936.*

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